The energy dependence of flow in Ni induced collisions from 400 to 1970A MeV

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Abstract

We study the energy dependence of collective (hydrodynamic-like) nuclear matter flow in 400-1970 A MeV Ni+Au and 1000-1970 A MeV Ni+Cu reactions. The flow increases with energy, reaches a maximum, and then gradually decreases at higher energies. A way of comparing the energy dependence of flow values for different projectile-target mass combinations is introduced, which demonstrates a common scaling behaviour among flow values from differerent systems.

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The study of nuclear matter over a wide range of temperatures and densities and the determination of the Equation of State (EOS) of nuclear matter continue to be of considerable interest [1]. Lacking the possibility of comprehensive studies of nuclear matter in bulk (as in neutron stars), one resorts to the study of transient, finite systems provided by nucleus-nucleus collisions (over a wide range of energy). It is now clear that the extraction of EOS information from nuclear collisions requires a comprehensive set of measurements of collision observables, which can be compared to realistic microscopic calculations involving the nuclear matter variables.

At GeV per nucleon energies, where the collision velocity exceeds that of nuclear sound, the collisions produce densities several times higher than ground state densities and exhibit compression-induced flow of nuclear matter [1]. However, it was not until the analysis of events from the 4π Plastic Ball/Wall [2] and Streamer Chamber [3] detector systems at the Bevalac that the matter flow characteristics could be studied and quantified for a range of systems and energies. More recently, at the Bevalac at LBNL, the EOS Collaboration carried out a comprehensive set of measurements over a wide range of energies, and projectile-target combinations [4]. Similar studies are underway at GSI in Darmstadt and, with lighter projectiles, by the DIOGENE Collaboration at Saclay [5]. EOS Collaboration data has been used to study flow for the $Au + Au$ system at lab energies ranging from 250 to 1150A MeV [6]. Particle flow for protons, deuterons and alpha particles has been determined, using the transverse momentum method [7]. The flow is found to increase with particle mass A, and with energy up to projectile energies of 1150A MeV where it tends to level out at values close to the Plastic Ball data [8].

Here we present analyses of recent EOS $Ni + Au$ data with energies between 400 and 1970A MeV and EOS $Ni + Cu$ data at energies of 1000, 1500 and 1970A MeV. This study with the Ni beam allows the use of higher energy per nucleon projectiles, and so extends the energy of our flow measurements beyond the 1150A MeV limit of the EOS $Au + Au$ data [6]. We also present a comparison of the flow values with predictions of a BUU model from Bauer *et al*. [9], and introduce a scaled flow which allows the comparison of flow data from a variety of projectile-target mass systems. In total, the data (supported by the calculations) provide the strongest evidence yet that, with increasing energy, flow reaches a maximum near 1000A MeV, and then declines.

The EOS Collaboration detector systems have been described in Refs. 4 and 6. The data presented here were obtained using the EOS Time Projection Chamber [10], situated in the magnetic field of the HISS Magnet. The TPC provides fairly unambiguous particle identification, as well as a measurement of momentum, for particles of charge up to $Z = 6$. Particle ID is ambiguous for rigidities above 2.4 GeV/c. Thus, some misidentification will occur and its effect is represented in the uncertainties. The target is just upstream from the TPC and this results in a large and nearly seamless acceptance. Laser beam calibrations provide a check of the corrections for B field inhomogeneities, and measurements of drift velocity. Simulations have been performed to study the geometrical acceptance of the detector and to provide acceptance corrections.

In the present experiment, the thickness of the Au target was 730 mg/cm^2 corresponding to about 1% interaction probability. The trigger was provided by a scintillator just downstream from the target. The MUSIC (Multiple Sampling Ionization Chamber) detector, downstream from the TPC, provided an on-line check on the threshold charge of the heaviest fragment allowed by the trigger. For this analysis, data for a wide range of impact parameters were taken. We used charged particle multiplicity as a measure of the collision centrality, and have adopted the Plastic Ball [8] convention by dividing the events into five multiplicity bins with bin M1 corresponding to the most peripheral and bin M5 having the most central events. For the $Ni + Au$ 400, 600, 1000 and 1970A MeV the numbers of events analyzed were 32k, 26k, 33k and 26k respectively. The $Ni + Cu$ 1000, 1500 and 1970 A MeV analyses were done on recently analyzed data sets of respectively, 35k, 19k and 48k events. For each event, the reaction plane was determined using the transverse momenta of the particles, as proposed by Danielewicz and Odyniec [7]. The plane is determined by the vector $\vec{Q} = \sum_i w_i \vec{p}_i^{\,t}$ and the incident beam direction. Here $\vec{p}_i^{\,t}$ is the transverse momentum of particle i, and w_i is a weighting factor defined to maximize the contribution of high rapidity particles to the $\vec{Q}$ vector determination. Normally, for symmetric collisions of equal A, w_i is taken to increase linearly with rapidity up to $w_i = \pm 1$ at $|y'_{\rm cm}| = \delta$ and to be constant at ± 1 for $|y'_{\rm cm}| \geq \delta$. Using the sub-event method of Ref. 7 we found the optimal reaction plane determination to be made with $\delta \simeq 0.7$. We also found that varying δ by 0.1 results in only a 1% change in the flow values. For the asymmetric $^{58}Ni + {}^{197}Au$, the nucleon-nucleon and nucleus-nucleus center of mass frames are different. There is therefore some ambiguity as to which reference frame to use for determining the weighting factors. We went through an iterative procedure as follows: We start out in the nucleus-nucleus cm frame, do the $\vec{Q}$ weighting in that frame, and then project the $\vec{p}_t$ of each particle onto the reaction plane. We refer to this projection as p_x for each particle in the event. Plotting the $\langle p_x/A \rangle$ (henceforth referred to as $\tilde{p}_x$) vs. rapidity for all events at a given energy then yields the typical S-shaped curves. These S curves do not cross the $\tilde{p}_x = 0$ axis at $y_c = 0$ where y_c here refers to the rapidity in the chosen frame, in this case the nucleus-nucleus cm frame. We next look at $\tilde{p}_x$ vs. lab rapidity and note where the curve crosses the $\tilde{p}_x = 0$ axis. This crossing rapidity defines the velocity of the new frame in which we do the next weighting. A couple of iterations yields a stable crossing value of y. Finally, we need to correct $\tilde{p}_x$ for the fact that we project onto an imperfectly known reaction plane. For this we use the sub-event method of Ref. 7. These corrections increase the $\tilde{p}_x$ values from 10% (for the more central $Ni + Au$ events) to 20% (for the more peripheral $Ni + Cu$ events).

Figure 1 shows the S-shaped plots of $\tilde{p}_x$ vs. y' for the four $Ni + Au$ systems and for multiplicity bin M4. Here, for the moment, we include only protons, for which we have unambiguous particle identification. Following the Plastic Ball analysis we define the flow, F, as the slope $(d\tilde{p}_x/dy')_{\tilde{p}_x=0}$ at the zero crossing (generally around $y' = 0.35$). The slope is calculated from a linear fit to the data. Similar F values are obtained using a cubic fit. The imperfect asymmetry of the S-curve with respect to the $\tilde{p}_x = 0$ axis is due to both the lower acceptance in the lower rapidities, as well as reflecting transverse momentum conservation in the asymmetric collision: The larger number of (mainly target) particles (both spectator and participant) at low rapidity, is balanced at higher rapidity, by fewer particles having larger average p_t values. From the geometrical acceptance studies we found that acceptance corrections on the flow values are on the order of 5% for the lower energy $Ni + Au$ 400A and 600A MeV systems . Flow value corrections above 600A MeV are negligible since the detector has full acceptance for the region where the fitting is performed.

In Figure 2 the extracted values of the slope, F (for protons), at $y'(p_x = 0)$ are plotted vs. projectile kinetic energy per nucleon and compared to the flow predicted by a basic BUU model [9]. This model does not include composite particle formation so the comparison is with the experimental proton F values. With the inclusion of bound protons (from d, t, etc.) the trend of the F values, as a function of energy, is similar. It should be noted that the BUU model used here does not include momentum dependent interactions. It is expected that adding these will increase the predicted BUU flow values, bringing them to better agreement with the data. The hard EOS BUU flow values appear to reach their maximum at a lower energy than the soft EOS. In this aspect the hard EOS BUU is closer to the energy dependence of the data. However, neither case gives quantitatively the energy dependence, and work on this aspect continues [11]. The main point here is that the BUU model does predict a rise and fall of flow. The energy dependence in Fig. 2 is consistent with the EOS $Au + Au$ proton flow data of Partlan *et al.* [6] and the Plastic Ball data [8] which show the flow beginning to plateau above 800A MeV.

We have studied other flow observables: the maximum value of $\tilde{p}_x$, the maximum value of F, regardless of the corresponding y value, and the sum $\sum \tilde{p}_x$, summed over all values for $y' > y'(\tilde{p}_x = 0)$. All of these observables give a flow energy dependence consistent with that for F. We have also analyzed the data using the reaction plane independent flow signal quantity [12] proposed by the FOPI group. In addition we have examined the flow angle dependence on multiplicity for the 4 energies. Both the flow angle and the FOPI signal show an energy dependence (rise and fall) similar to that of F in Fig. 2.

It can be argued that flow should be determined from the laboratory rapidity, y, rather than from reduced rapidity, $y' = y/y_{\text{beam}}$. Then flow becomes $F_y = d\tilde{p}_x/dy = F/y_p$ where

y_p is the projectile beam rapidity in the lab frame. Plotting F_y vs. energy we find that the rise of flow is reduced while the decline becomes more significant.

The rise and fall of flow is explicable or at least qualitatively reasonable. As energy increases, the nucleon-nucleon cross sections become more forward peaked. The mean transverse momentum at first rises rapidly with energy and then is almost constant above $p_z \simeq 2$ GeV/c. Thus, flow as a manifestation of multiple scattering effects should eventually fall as p_z continues to increase.

It is of great interest to compare the flow values for a wide range of data. To allow for different projectile-target (A_1, A_2) mass combinations, we divide the flow value by $(A_1^{1/3} + A_2^{1/3})$ and call $F_S = F/(A_1^{1/3} + A_2^{1/3})$ the scaled flow. In recent calculations of flow [13], the authors use an $F/A^{1/3}$ scaling for symmetric systems, and argue that, for a given energy, the flow should scale with collision (compression) time. This suggested the $(A_1^{1/3} + A_2^{1/3})^{-1}$ scaling used here. Figure 3 shows a plot of F_S vs. energy per nucleon of the projectile. We include here data from the EOS experiment (solid points), along with values derived from other experiments [8,14–16] for a variety of energies and mass combinations. As closely as possible the data selected correspond to Plastic Ball multiplicity bins M3 and M4 or to an equivalent range of impact parameters. For the EOS and Plastic Ball data all the isotopes of $Z = 1$ and 2 are included, except for [16] where the data is for Z=1 and multiplicity bin M3. The Streamer Chamber data [14,15] normally include all protons, whether free or bound in clusters. Generally the flow values using all isotopes of $Z = 1$ and 2 are $10 - 20\%$ larger than those for protons. In Fig. 3 the scaled flow values, F_S, follow, within the uncertainties, a common trend with an initial steep rise and then an indication of a gradual decline. The Plastic Ball data are quoted with fairly small statistical uncertainties, $\simeq 4-7\%$, about twice the size of the data points in Fig. 3. For the $Ar + Pb$ [14] and $Ar + KCl$ [15] Streamer Chamber data, we estimated the flow and statistical uncertainties from the $\tilde{p}_x$ vs. y data plots, for the appropriate multiplicity ranges. Our estimated uncertainties for these flow values are in the range of 15-23%. The 1800A MeV $Ar + KCl$ Streamer Chamber data, as analyzed in Ref. 7, produce a very large flow and scaled flow value ($F_s \simeq 93$ MeV/c per nucleon which is off the plot scale and not included in Fig. 3).

In summary, we have determined the nucleon flow for Ni induced collisions over an energy range of 400 to 1970A MeV. For these Ni systems flow, F, as measured by the change with rapidity of the average transverse momentum, rises with energy, and then declines. Comparison of our flow results with flow data from other mass systems is made by introducing a scaled flow, $F_S = F/(A_1^{1/3} + A_2^{1/3})$ which exhibits a nearly universal flow energy dependence.

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FIGURES

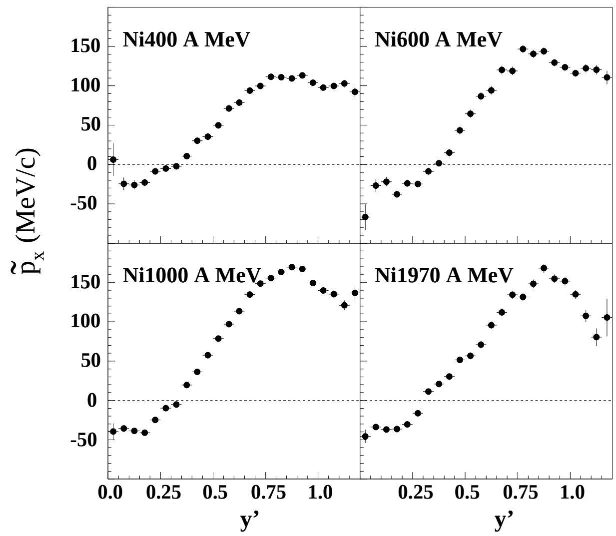

FIG. 1. S curves for the four $Ni + Au$ energies, using protons only in multiplicity bin M4. $\tilde{p}_x$ is the average of the x component of the momentum (see text). y' is the rapidity in the lab frame scaled by the rapidity of the beam.

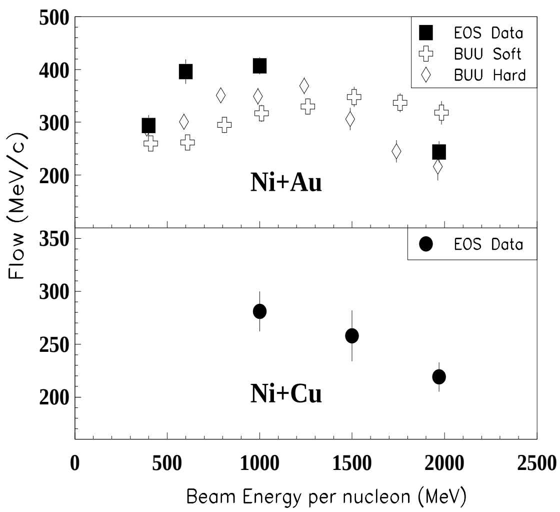

FIG. 2. Proton flow as a function of beam energy per nucleon in multiplicity bin M4. The top panel is for $Ni + Au$ EOS data. The solid symbols are the flow values from the graphs in Fig. 1 while the open symbols are for soft and hard equation of state BUU $Ni + Au$ calculations with an equivalent impact parameter distribution. The bottom panel consists of flow values determined from $Ni + Cu$ EOS data.

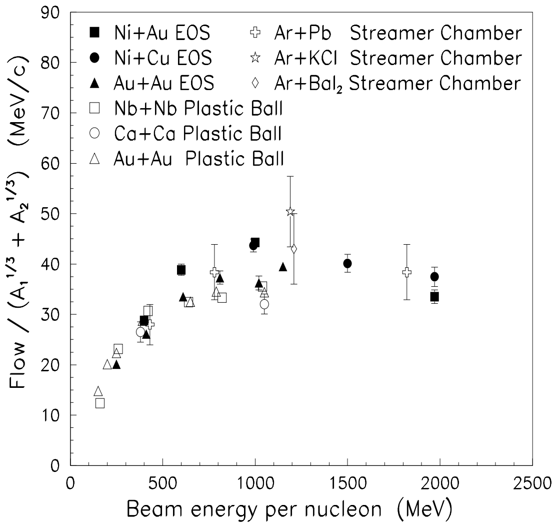

FIG. 3. Scaled flow values vs. beam energy per nucleon for different projectile-target systems for Plastic Ball multiplicity bins 3+4. In the EOS and Plastic Ball data all isotopes of Z=1,2 are included. For the Streamer Chamber all free and bound protons are included. To improve the distinction between data points at the same beam energy, some of the beam energy values have been staggered around by as much as 20 MeV.